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A Study of Air/Space-borne Dual-Wavelength Radar for Estimation of Rain Profiles

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ABSTRACT

In this study, a framework is given by which air/space-borne dual-wavelength radar data can be used to estimate the characteristic parameters of hydrometeors. The focus of the study is on the Global Precipitation Measurement (GPM) precipitation radar, a dual-wavelength radar that will operate in the Ku (13.6 GHz) and Ka (35 GHz) bands. A key aspect of the retrievals is the relationship between the differential frequency ratio (DFR) and the median volume diameter, D_0, and its dependence on the phase state of the hydrometeors. It is shown that parametric plots of D_0 and particle concentration in the plane of the DFR and the radar reflectivity factor in the Ku band can be used to reduce the ambiguities in deriving D_0 from DFR. A self-consistent iterative algorithm, which does not require the use of an independent path-attenuation constraint, is examined by applying it to the apparent radar reflectivity profiles simulated from a drop size distribution (DSD) model. For light to moderate rain, the self-consistent rain profiling approach converges to the correct solution only if the same shape factor of the Gamma distributions is used both to generate and retrieve the rain profiles. On the other hand, if the shape factors differ, the iteration generally converges but not to the correct solution. To further examine the dual-wavelength techniques, the self-consistent iterative algorithm, along with forward and backward rain profiling algorithms, are applied to measurements taken from the 2nd generation Precipitation Radar (PR-2) built by the Jet Propulsion Laboratory. Consistent with the model results, it is found that the estimated rain profiles are sensitive to the shape factor of the size distribution when the iterative, self-consistent approach is used but relatively insensitive to this parameter when the forward- and backward-constrained approaches are used.

Key words: rain rate, dual-wavelength radar, raindrop size distribution, and GPM

1. Introduction

Radar has been shown to be one of the most powerful means to measure rainfall rate. Methods that directly relate a radar measurable such as the radar reflectivity factor, Z, to the precipitation rate, R, are widely used to monitor and estimate the storm evolution and intensity in a variety of storms. Many radar applications use a single wavelength in the S or C band. In these cases, the wavelength is much larger than the hydrometeor sizes so that the assumption of Rayleigh scattering is appropriate for the analysis. An abundance of studies and observations have suggested that the drop size distribution (DSD) is well characterized by the Gamma distribution (Gorgucci et al., 2001, 2002; Bringi et al., 2002), which generally has more than two independent parameters. Theoretically, a single wavelength radar is unable to account fully for the variability arising from different meteorological conditions. It is therefore not surprising to see the existence of many $Z-R$ relations reported in the literature (see Gunn and Marshall, 1958; Smith, 1984; Boucher and Wieler, 1985; Matrosov, 1992).

Dual-wavelength radar has shown promise to improve the accuracy for estimates of the microphysical properties of hydrometeors if one or both wavelengths operate in the non-Rayleigh region (Matrosov, 1992; Meneghini et al., 1992; Liao et al., 1997; Mardiana et al., 2003). A spaceborne radar operating in the Ku (13.8 GHz) and Ka (35 GHz) bands has been proposed as one of the core instruments for the Global Precipitation Measurement (GPM) mission (Iguchi et al., 2002) and will serve as a calibrator for other instruments aboard the GPM satellite in mapping precipitation globally. However, the radar returns suffer

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from attenuation while propagating through the rain, cloud and mixed-phase precipitation. This attenuation not only complicates the radar retrieval of rain but also affects the accuracy of the algorithms if the attenuation is not properly corrected for.

In this study, we focus on dual-wavelength air/space-borne radar techniques for the estimation of characteristic parameters of hydrometeors. Having described the results of how the dual-wavelength measurements are linked to the DSD parameters, a self-consistent iterative approach for deriving the hydrometeor profile is numerically examined based on the simulation of the GPM spaceborne radar returns. Analysis of the results is also given. To make an assessment of the dual-wavelength techniques, the self-consistent algorithm, along with forward and backward rain-profiling algorithms, is applied to the measurements taken from the PR-2 airborne radar over stratiform rain.

2. Framework of dual-wavelength techniques

The average received power P by the radar from hydrometeors at range r (see Battan, 1973) is

$$P = \frac{C|K_\mathrm{w}|^2 Z \exp(-2\int_0^r k dr)}{r^2} , \tag{1}$$

where C is the radar constant and Z the effective radar reflectivity factor of the hydrometeors at wavelength λ, which can be expressed as

$$Z = \frac{\lambda^4}{\pi^5 |K_\mathrm{w}|^2} \int_0^\infty N(D)\sigma_\mathrm{b}(D,\lambda) dD , \tag{2}$$

where $N(D)$ is the particle size distribution and $\sigma_\mathrm{b}(D,\lambda)$ the backscattering cross section of a particle with diameter D. K_w, the dielectric factor, is used to designate $(m^2-1)/(m^2+2)$, where m is the complex refractive index of water. By convention, $|K_\mathrm{w}|^2$ is taken to be 0.93. The quantity k in Eq. (1) is the specific attenuation describing propagation loss due to scattering and absorption by hydrometeors along the path and is given by

$$k = \int_0^\infty N(D)\sigma_\mathrm{e}(D,\lambda) dD , \tag{3}$$

where $\sigma_\mathrm{e}(D,\lambda)$ is the extinction (or total) cross section of the particle. Note that the factor of 2 in Eq. (1) accounts for the 2-way attenuation. Finding a solution to the parameters of the $N(D)$ from Eq. (2) is an inverse problem that can be solved by use of radar measurements.

The hydrometeor size distributions can be conveniently described by the Gamma function. A form of the Gamma size distribution of $N(D)$, used widely in the retrieval of the microphysical properties of hydrometeors, is expressed as

$$N(D) = N_0 D^\mu \exp\left[-(3.67+\mu)\frac{D}{D_0}\right] , \tag{4}$$

where N_0 is constant, D_0 the median volume diameter of the particle and μ the shape factor. The number concentration, N_T, can be expressed in terms of these variables by:

$$N_\mathrm{T} = N_0\Gamma(\mu+1)/G^{\mu+1} , \tag{5}$$

$$G = (3.67+\mu)/D_0 , \tag{6}$$

where Γ is the Gamma function. The radar differential frequency ratio (DFR) in dB, denoted by R_DF, describing the difference of the radar reflectivity at two wavelengths, is defined as

$$R_\mathrm{DF} = 10\log(Z_1/Z_2) , \tag{7}$$

where Z_1 and Z_2 are the radar reflectivity factors at wavelengths of λ_1 and λ_2. The DFR is independent of the N_0 as can be inferred from Eqs. (2), (4), and (7).

5. Summary

A description of several dual-wavelength techniques is given for the retrieval of rain profiles. The results, linking the radar measurables to the DSD parameters, are computed for the GPM radar that will operate in the Ku and Ka bands. The air/space-borne dual-wavelength radar profiling algorithms are discussed, and an iterative backward approach is numerically examined for its validity. We conclude that, for light to moderate rain rates, the iterative procedure converges to the correct solution if the same DSD parameters (i.e., μ and temperature) are used both to generate and retrieve the radar profiles, but does not converge to the true solutions if the form of the DSD is not chosen correctly. Cloud water, if its attenuation is not accounted for properly, may also introduce errors in the retrieval of DSD parameters by use of the self-consistent iterative method. To make an assessment of the dual-wavelength techniques, the various rain-profiling algorithms are applied to measurements taken from the PR-2 during CAMEX-4 in 2001. Comparisons of the results show that rain profiles estimated from the forward and backward approaches are not sensitive to the assumed shape factor of the DSD Gamma distribution, but the self-consistent method is. In future studies, the bright band and cloud water will be included in the simulations to test further the various methods that have been proposed.